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A Method for the Quantitative Assessment of Performance of Alternative Designs in the Accidental Condition

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Abstract

Following various high profile incidents, the role of residual strength in accident scenarios is becoming more important in the design process, in particular when considering the effects on the structural integrity of competing designs. Accidental damage of ships can occur in any number of ways including damage due to Collision and Contact, Grounding, Non- accidental structural failure, Fire and Explosion.

Risk based design of ships is becoming an accepted design process for most ship types providing a rational basis for making decisions in the design, operation and regulation of these ships. One area that has become of much greater concern to the design and operation of ships is that of accidental damage. This paper addresses the question of how to combine probabilities of failure and probabilities of occurrence into a useful process for the quantitative assessment of performance of alternative designs in the accidental condition

Keywords

Residual strength of a ship's hull; Accidental damage; Structural reliability; Probability of failure.

Introduction

Risk based design of ships is becoming an accepted design process for most ship types, providing a rational basis for making decisions in the design, operation and regulation of these ships. One area that has become of much greater concern to the design and operation of ships is that of accidental damage. Accidental damage to ships can occur in any number of ways but generally damage due to collision and grounding are of the most concern. Following high profile incidents, such as the *Herald of Free Enterprise*, the *Estonia*, *Exxon Valdez*, and more recently, the *Sea Empress*, the *Prestige* and the *Sea Diamond*, comparison of the response of alternative designs to accident scenarios is becoming more commonplace in the design process, in particular when considering the effects on the structural integrity of the competing designs.

The damaged case represents a considerably different challenge to the general design condition. Different hull girder loadings and the loss of structural integrity need to be accounted for. Structural reliability methods can be used to develop the probability of failure for each design and each individual accident case. Each individual accident scenario can also have an individual probability of occurrence associated with it. However to provide the design team with useful data, a range of accident scenarios need to be considered, leading to the question of how to combine this range of probabilities of failure with probabilities of occurrence, into a useful process.

Probabilities of failure and probabilities of occurrence are combined, within this study, into a potentially useful process for the quantitative assessment of performance of alternative designs in the accidental condition. A methodology has been developed and case studies for two ships, an Aframax tanker, and a VLCC tanker, are presented for a series of developed accidental damage scenarios. Damage statistics are based upon those developed for use by the IMO and other data developed by the European Union funded project Pollution Prevention and Control (POP&C).

Probability of Occurrence of Accidental Damage

Damage Statistics

Accident scenarios typically include Collision and Contacts (or Allisions), Grounding, Non-accidental structural failure, Fire and Explosion. The scenarios define the situations that will affect the risk to the ship and/or the environment e.g. a major pollution incident. The scenarios should represent as closely as possible actual situations that could be encountered by ships. Some incidents have major implications to the ship and or the environment but only have a very small likelihood of occurring whereas others have smaller impacts but potentially occur much more frequently. Therefore the probability of occurrence should be taken into account.

The accident scenarios, and their associated probability of occurrence, are typically derived using the following approaches:

- Statistics from historical data
- Expert opinion
- First principle tools

Much work into the identification of scenarios and the probability of occurrence of incidents has been undertaken for Aframax Tankers by Papanikolaou *et al* (2005) within the POP&C project, by developing a database of historical incident data from which incident statistics could be developed. In combination with relevant "fleet at risk" data, the incident rates per ship year could be calculated. While analysis of historical data sources can be a useful tool, sufficient data is not always available for the analysis and expert judgement is often used in risk analysis, as discussed by Delautre *et al* (2005). The extent of damage and the location of the damage will also have a probability associated with each as discussed later in this paper.

Probability of Occurrence

From the POP&C work the following incident rates are taken. These rates are specific to Aframax tankers but similar information could be developed for other vessel sizes and types. For evaluation of new Aframax vessels the most recent rates, 1999-2003, shown in Table 1, are most relevant.

Table 1: Incident Rates

Incident type	Average Incident Rates Per Shipyears
Structural Failure	1.82E-03
Collision	4.41E-03
Contact	1.48E-03
Grounding	3.64E-03
Fire	1.83E-03
Explosion	1.84E-03

The structural failure analyses considered within this work, assume rupture of hull structure and thus the incident rates need to be adjusted for the probability of loss of watertight integrity (LOWI), and associated extents of flooding, given the basic event. The POP&C project provides the rate of LOWI (for Aframax tankers) for the various accident types as shown in Table 2.

Table 2: Probability of LOWI

Incident type	% of Incidents where L.O.W.I. occurred
Structural Failure	29.8
Collision	16.7
Contact	23.8
Grounding	18.6
Fire	1.00
Explosion	12.8

Probability of Failure

Structural Reliability Analysis

The construction of a typical risk model requires that the probability estimates for the various events in the model are determined. Traditional approaches, using historical data or expert judgement, whilst applicable as previously discussed in this paper, are not particularly applicable to developing the probability of failure of a hull structure and would not be able to respond to small but significant changes in variables such as plate thickness or hull component loadings.

Structural reliability theory attempts to estimate the probability that a structure will fail at some time when in service and includes the uncertainties associated with the estimates of the strength and loadings appropriately calculated. It therefore accounts for the natural variations in the load and strength components arising from the stochastic nature of the ocean and variability in geometric and material properties of the structure, and the inherent uncertainty with the actual engineering calculation processes themselves. As discussed by Collette *et al* (2005), reliability methods express the problem being investigated in the form of a limit state equation which relates the loading and strength variables in such a manner that structural failure occurs when the result of the limit state equation is less than zero.

Fully determining the probability that an equation of stochastic variables will be less then zero is an extremely complex problem and one that results in structural reliability theory being implemented in a simplified manner. Melchers (2002) discusses that the result of this simplification of the otherwise complex mathematics in determining the probability of failure, combined with limited knowledge of the variation of material, strength and loading properties related to the structure, and the conclusion is that the determined probability of failure is a "nominal" value.

Methods for considering the probabilities of failure of the hull girder due to overall collapse in bending are discussed by Downes and Pu (2005), and Das and Dow (2000) among others.

Longitudinal Hull Girder Strength

Overall bending of a ship's hull girder is a very important failure mode, which is normally catastrophic and has severe consequences. It is thus of great importance to accurately predict the ultimate strength of hull girders so that an adequate but not excessive safety margin for this failure condition can be ensured at the ship design stage. The methods for estimating the ultimate strength of hull girders could be classified as empirical methods (Paik *et al* 1996), progressive collapse analysis (Smith 1977), and numerical methods, such as finite element methods. Amongst these methods, progressive collapse analysis is preferred in practice because it is reasonably accurate and computationally efficient (Jensen *et al* 1994).

Empirical methods are typically based upon the conventional section modulus of the midship section with various procedures suggested for the strength calculation. They develop only the predicted ultimate strength value and cannot give any further information about the collapse mechanism of the hull girder. One method is the single step approach given in the Common rules for Double Hull Oil Tankers (IACS, 2006), January 2006 edition which has been adopted by IACS and came into force on the 1st April 2006.

Finite Element methods have been applied to various hull girder analyses. Both geometric and material nonlinearities can be considered, however the effects of residual stress are often neglected. The evaluation of the ultimate longitudinal strength of a hull girder is still an extremely daunting task due to the amount of data preparation and computational time required. The length of the model and the application of boundary conditions are of particular importance. This approach is more suited to the final design validation stage.

Progressive collapse Moment-Curvature methods idealise the transverse section of the hull girder into specific elements as developed by Smith (1977). Bending occurs about the instantaneous conventional neutral axis, which is initially calculated using elastic analysis assumptions. The section is also assumed to remain plane. Curvature, C, is then applied about this axis. At each increase of curvature the strain in each individual element, ε_i, can be calculated.

$$\varepsilon_i = Cy_i \tag{1}$$

where y_i is the vertical distance of ith element from the neutral axis.

The corresponding axial stresses (σ_i) are then found from the relevant stress-strain curves. Hard spots, e.g. joint regions, between plating in a structure can be considered to have sufficient stiffness to resist premature buckling and will follow an elastic-perfectly plastic path in both tension and compression. The corresponding overall current vertical bending moment capability is then calculated using a summation process.

$$M = \sum_{i=1}^{n} \left(\sigma_i, A_i, y_i\right) \tag{2}$$

where M is the vertical bending moment, σ_i is the stress in the i^{th} element and A_i is the cross-sectional area of i^{th} element

As the applied curvature is incrementally increased, the corresponding position of the neutral axis must be altered in order to maintain overall equilibrium of the structure. This can be calculated by checking the longitudinal force equilibrium over the whole transverse section and hence adjusting the currently assumed neutral axis until the change in position is less than 0.0001m

$$F_i = \sum_{i=1}^{n} A_i \sigma_i \tag{3}$$

Where F_i is the total force on the section.

In a damaged ship, the hull may become unsymmetrical due to this damage, which will therefore result in unsymmetrical bending occurring. In addition, it can be typically assumed that flooding has occurred to some extent and that this is likely to induce an angle of heel and hence also induce horizontal bending. These considerations should be accounted for in the analysis of the ultimate longitudinal strength. Wang *et al* (2002) considered the longitudinal hull girder strength of a range of ships in the damaged condition.

The ultimate longitudinal strength of a hull girder is typically analysed at the point in which maximum bending, and hence zero shear force, occurs. Therefore the effects of shear and torsion are typically neglected from the analysis procedure. In the damaged case, shear forces in the area of the damage can be significant and influence the position of collapse. Yao *et al* (2004) suggested a methodology for considering the effects of warping on the ultimate strength when using 2-D approach. The influences of shear stress were considered in two ways; the influence on buckling and yield strength of the structural components and secondly, the influence of warping on the stress distribution in the cross-section.

Loadings

The loads acting on the hull girder are primarily due to the ship's own weight, cargo, buoyancy, and operations at sea. As discussed by Ayyub *et al* (2002), the loads can be grouped into three main categories.

- Stillwater loads
- Wave loads
- Dynamic Loads

Stillwater loads can be evaluated from proper consideration of the mass distribution over the ship length, the variability in the cargo loading and the buoyancy of the ship.

Previous studies on the wave loading on damaged ships have been fairly limited, and the two of most notable studies have been concentrated on passenger vessels. As part of the EU 4th-Framework project DEXTREMEL, which investigated the structural safety of a typical Ro-Ro ferry under extreme conditions including damage, an extensive study was carried out on the response of the ship (Chan *et al*, 2003). This included the formulation of a new time-domain nonlinear strip theory for predicting the wave induced loading at zero forward speed, and a comparison of the predicted loads with those from model tests. The numerical theory agreed well with the test results in most cases, and the wave loads were higher in the damaged condition than those in the intact condition.

Similar studies were carried out for a cruise ship in a joint U.S. Coast Guard and Ship Structures Committee project (Tagg & Akbar, 2004, Iversen, Moore & Tagg, 2006). In the first study, several damage scenarios were investigated for a large cruise ship. Again, a midship damage case led to reduced still water hogging bending moments that were judged to be the most critical for survival given the weak compressive strength of the upper decks. In the second study the possibility that midship flooding would lead to sagging moments was investigated. Sea loading was estimated by the linear strip theory program SMP originally developed by the US Navy. Based on the results of the EU 5th Framework HARDER project, a 3.5m significant wave height was selected for the survival condition, which should be equal to or greater than the actual wave height for 98% of the damage cases.

Large amplitude motions and resulting structural responses, which cannot be accurately predicted by linear theory, are key issues for determining maximum demand and subsequent assessments of ultimate hull girder strength of intact ship and residual strength of damaged ship in extreme wave conditions. In particular nonlinear effects associated with large amplitude motions and loads are much pronounced for RoRo hull having fine form with large bow flare, as the water plane area of the damaged RoRo hull varies significantly as the vessel oscillates. Moreover, the wetted body sections become asymmetrical during roll motion and flood water dynamics are present inside a damaged compartment. As a result there is a need to use techniques being capable to take into account these nonlinear effects. Although the nonlinear boundary element technique is applicable to solving full nonlinear ship motion problem, its computational cost is prohibitively expensive in practical design office applications.

The added mass approach is one method that can be used for modelling one effect of the damage. In this approach, the seawater which floods into the vessel is assumed to become part of the vessel's mass, and to move with the vessel. For calculating the hydrodynamic forces, the damage opening is assumed to have negligible impact on the overall hydrodynamic properties of the hull. This approach should be accurate for damage extents which are small compared to the size of the tanks which are breached. For larger breaches, an alternative approach would be to remove the damaged tank and all of its mass from the vessel, and remove its surface area from the hydrodynamic model. However the hydrodynamic interaction between the waves and the structure of the opening remains after removing the tank from the ship hull, which needs to be modelled.

Method for Integration of Probabilities

The approaches described in the previous sections develop detailed information about the damage extent, damage location, loading, and ultimate longitudinal hull girder strength, which is necessary for structural reliability analysis to be undertaken for each actual or assumed damage scenario.

In the design evaluation case, information on damage extent probabilities is used to modify the initial probability of failure by also taking into account the probability of occurrence of damage, and details of its probability of extent and location.

In the POP&C work, damage extent statistics are used to develop damage cases for evaluating the potential oil outflow performance of alternative designs. These assessments potentially involve thousands of feasible damage cases which would be impractical to evaluate using the structural reliability methods described here. Instead it is proposed that a representative set of damage cases be developed that explore major examples of damage and to assign relative probabilities to each case based upon the damage extent statistics that are available. Stumpf and DeLautre (2006) established a set of damage cases that test the structural capability of tankers. These were largely based upon damage extents consistent with MARPOL criteria. This set has been expanded by the authors to account for additional basic events including Grounding, Non-Accidental Structural Failure (NASF), Fire and Explosions. Table 3 provides the damage cases selected with a short description of their extent. For the purpose of this work, damage was assumed to have occurred at the midships. Further details of these cases can be found in Downes *et al* (2006).

These damage cases have been assigned to the basic events as shown in Table 6 in the Results section. Within each basic event grouping, e.g. collision, grounding, etc. the damage extent statistics have been combined with engineering judgment to develop relative weighting for each case. For NASF and Explosion the weighting is assumed to be uniform. Collisions and Contacts have been combined into a single category as the damage extent statistics do not distinguish between them. Fires have been discarded due to the low probability of LOWI.

Table 3: Damage Cases for Aframax Tanker.

Case	Location	Vertical Extent (m)	Horizontal Extent (m)
1	Side Shell	9.345	-
2	Side Shell + Inner Side Shell	9.345	2.50
3	Bilge	6.98	1.60
4	Bottom Shell	-	4.25
5	Bottom Shell + Inner Bottom	2.50	4.25
6	Bottom Shell + Bilge	2.00	4.675
7	Inner Bottom	-	4.25
8	Inner Side Shell	9.345	-
9	Hopper Joint	0.2	0.6
10	Deck - small	-	5.94
11	Deck - large	-	19.44
12	Side Shell above Bilge	14.445	2.50
13	Side Shell including Bilge	21.00	2.50
14	Full Side of Ship	21.00	8.00
15	Bottom Shell	-	19.44
16	Bottom Shell + Inner Bottom	2.5	19.44
17	Keel	-	2.127
18	Keel + Inner Bottom	2.5	2.127

The suggested methodology is given in Equation 4.

$$P_{f_{MOD}} = P_b \times P_{LOWI} \times P_D \times P_f \tag{4}$$

Where

P_{fMOD} = Modified Probability of Failure.

P_b = Probability of Basic Event

P_{LOWI} = Probability of LOWI

P_D = Probability of Damage Extent.

P_f = Probability of Structural Failure.

This equation could be further modified to account for the severity of the incident. This would allow for scenarios other than loss of ship to be considered in more detail.

Case Studies

Case studies on two ships have been undertaken; an Aframax tanker and a VLCC tanker. Both ships are double hull construction and their particulars are given in Table 4.

Table 4: Ship Particulars

	Aframax	VLCC
Length BP (m)	239.00	320.00
Breadth (m)	44.00	60.00
Depth (m)	21.00	30.50
DWT (MT)	112,700	320,000
Arrangement	6x2	5x3

Analysis of the ultimate longitudinal hull girder strength of the ships has been undertaken for both the intact condition and for 18 damage cases. The damage cases are described in Table 3 using the Aframax Tanker as an example and were appropriately scaled for the VLCC tanker.

The Stillwater loading was calculated using the Herbert Software Solutions Inc HECSALV™ software. The effects of flooding of both cargo spaces and void spaces, and the corresponding oil outflow were incorporated into the analysis. Stillwater bending moments can be significantly increased due to flooding. Damage cases developed from the damage extents for Aframax tankers in POP&C were evaluated to determine the stillwater bending moment in the damaged condition. The change in bending moment compared to the class allowable is shown in Fig. 1. For example, in the full load condition 10% of the cases lead to an increase in sagging moment of 25% or more of the allowable stillwater bending moment.

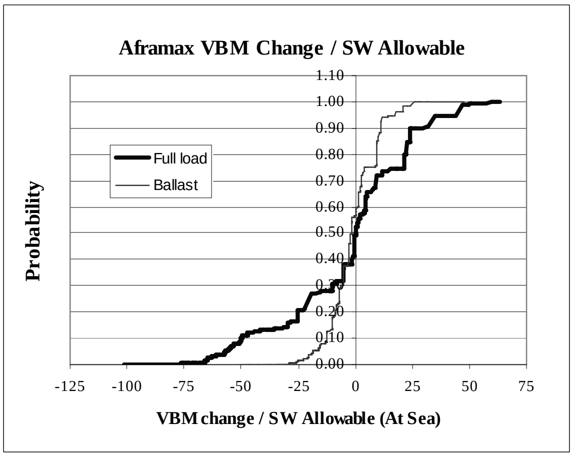

Fig. 1: Change in Stillwater bending moment due to flooding after side damage

The analysis of wave induced bending moments was initially limited to the vertical bending moment, which is typically the dominant loading in head seas, using linear response theory and the added mass model for flooding water (Collette *et al* 2005). A range of damage cases were considered as shown in Table 5. These cases cover a wide range of side damage, raking damage and bottom damage.

Table 5: Damage Loading Cases

Damage Case	Tanks Damaged
1	FP
2	FP, 1C-S, 1B-S
3	All Tanks 1&2 - S
4	All Tanks 3&4 - S
5	All Tanks 5&6 – S, Pump room, Slop, CO Sludge, Void
6	SG, ER
7	1-3B-S
8	1-6B-S
9	1-2 B tanks, FP

The comparison of the intact condition and the different damage cases RAOs for vertical bending moment are shown in Fig.2 Comparison of RAOs for Aframax Damage Cases

where it can be seen that the RAO peak value increases, with increasing damage and heel. It can also be seen however, that there is no significant difference between the RAOs due to the effects of damage.

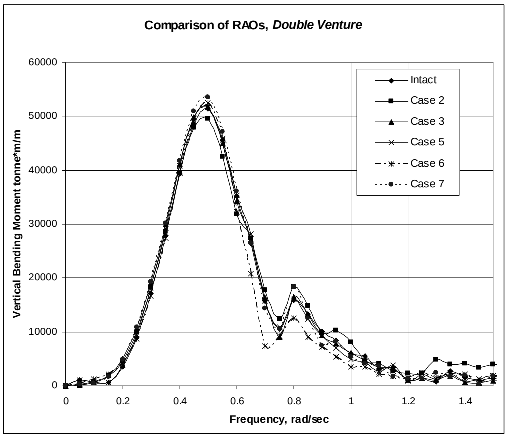

Fig.2 Comparison of RAOs for Aframax Damage Cases

This study indicated that the change in global hull loading may be much smaller for tankers than for Ro-Ro ferries and cruise ships. Furthermore, the deck of a tanker, while still usually weaker in compression than the bottom, is not as lightly built as the upper decks of a passenger vessel.

Table 6 Combined Probability of failure for Aframax and VLCC tankers

					Aframax	VLCC	Aframax	VLCC
Case		Prob of Damage Extents	Prob of Event per Ship Year	Prob of LOWI	Probability of Failure (Structural)		$P_{f\ MOD}$	
1	Collision*	0.23	5.89E-03	0.203	1.53E-03	2.01E-05	4.20E-07	5.52E-09
2	Collision*	0.22	5.89E-03	0.203	2.86E-03	1.52E-05	7.50E-07	3.99E-09
12	Collision*	0.53	5.89E-03	0.203	2.90E-03	4.54E-05	1.83E-06	2.87E-08
13	Collision*	0.01	5.89E-03	0.203	3.68E-03	6.57E-05	4.39E-08	7.84E-10
14	Collision*	0.01	5.89E-03	0.203	2.31E-03	3.41E-04	2.76E-08	4.07E-09
3	Grounding	0.23	3.64E-03	0.186	1.09E-03	9.88E-06	1.67E-07	1.51E-09
4	Grounding	0.22	3.64E-03	0.186	1.23E-03	1.22E-05	1.80E-07	1.79E-09
5	Grounding	0.05	3.64E-03	0.186	1.69E-03	2.01E-06	6.16E-08	7.33E-11
6	Grounding	0.15	3.64E-03	0.186	1.20E-03	1.14E-05	1.20E-07	1.14E-09
15	Grounding	0.15	3.64E-03	0.186	4.75E-03	2.24E-05	4.83E-07	2.28E-09
16	Grounding	0.04	3.64E-03	0.186	8.95E-03	3.31E-06	2.26E-07	8.38E-11
17	Grounding	0.03	3.64E-03	0.186	3.54E-03	8.20E-05	6.95E-08	1.61E-09
18	Grounding	0.14	3.64E-03	0.186	1.47E-03	2.57E-05	1.38E-07	2.42E-09
7	NASF**	0.33	1.82E-03	0.298	2.13E-03	1.65E-06	3.85E-07	2.98E-10
8	NASF**	0.33	1.82E-03	0.298	2.79E-03	2.53E-06	5.04E-07	4.57E-10
9	NASF**	0.33	1.82E-03	0.298	2.11E-03	1.56E-06	3.81E-07	2.83E-10
10	Explosion	0.50	1.84E-03	0.128	3.49E-03	7.03E-06	4.11E-07	8.28E-10
11	Explosion	0.50	1.84E-03	0.128	1.88E-03	1.67E-04	2.21E-07	1.96E-08
						Totals	6.42E-06	7.55E-08

*Including Contacts. **Non-Accidental Structural Failure

Results

The probability of failure was calculated using a FORM methodology in conjunction with the singular progressive collapse limit state function. Combining the probabilities of failure with the basic event probability, the probability of LOWI, and the relative weighting within each of the basic events leads to an overall probability (P_{fMOD}). This could then be converted to a reliability index to be used for comparison between designs. Table 6 shows the analysis of the two case study vessels.

The POP&C Project considered 5 different sea areas for the location of potential incidents around the European Coastline. The assessment in this paper has been made, for both vessels, for the full load condition only, using sea conditions representing the Bay of Biscay which was the most severe of the areas considered by the POP&C project.

Preliminary calculations have indicated that the probability of failure is sensitive to the wave loading, however further investigations are needed to confirm this.

It can be seen that there is a difference between the results for the Aframax and the VLCC. This may be due to larger vessels being less sensitive to larger wave loading than smaller vessels.

Conclusions

The question of how to combine probabilities of failure and probabilities of occurrence into a useful process has been addressed by developing a methodology for the quantitative assessment of the relative performance of alternative designs in the accidental damaged condition.

This methodology has been used in the analysis of an Aframax tanker and of a VLCC tanker. The combined probability of failure (P_{fMOD}) was developed from the probability of failure using a FORM based analysis, the probability of damage extent, the probability of LOWI and the probability of the event per ship year for each of the postulated damage scenarios.

It should be noted that the developed probability of damage extent, the probability of LOWI and the probability of the event per ship year for each of the damage scenarios are specific to the Aframax fleet. It has been used for the VLCC to show the application of the methodology and such data could be further developed for the VLCC fleet.

Whilst this study considered tankers, there is no reason that similar data couldn't be developed for the analysis of other ship types such as Ro-Ro's or passenger ships.

The resulting combined probabilities (P_{fMOD}) were developed and it is shown how alternative designs can then be quantitatively compared for design development purposes.

This analysis considered hull girder bending only, however the procedure could be applied when considering other design tradeoffs such as comparison of scantlings, spacings or framing schemes etc. This would require modification of the limit state used when developing the probability of structural failure (P_f)

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